



CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Building End Use Energy Efficiency

**CONTROL OF ON-OFF EQUIPMENT IN
BUILDINGS**

FEASIBILITY ANALYSIS

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to \$62 million of which \$2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to \$75,000 for promising proof-of-concept energy research.

PIER funding efforts are focused on the following six RD&D program areas:

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
 - Appendix A: Final Report (under separate cover)
 - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:

<http://www.energy.ca.gov/research/innovations>

or contact the EISG Program Administrator at (619) 594-1049 or email

eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at

<http://www.energy.ca.gov/research/index.html>.

Executive Summary

Introduction

Equipment used to control process variables such as temperature in buildings often operate by cycling on and off (or between stages if more than one “on” state) rather than as continuously modulating. Examples of such equipment include small to mid-sized packaged air-conditioning systems, furnaces, chillers operating at low loads, cooling tower fans, and some types of electrical heaters. On-off control units normally start and stop equipment when the process variable (e.g., space temperature) crosses a level. There are a number of disadvantages to using level-crossing logic. One disadvantage is that it is difficult to control the variation in the process variable with level-crossing logic, even if it is implemented digitally, because of the phase lag of the process. Another disadvantage is that level-crossing logic is not well suited for staged operation in which there exists more than one “on” state. A third disadvantage of level-crossing logic is that it makes the coordination of multiple units difficult.

This project developed and tested the feasibility of a new control strategy for the operation of "on-off" and staged equipment in buildings using computer simulation methods. Specifically, it developed the control logic so that it could be used to coordinate the operation of multiple units, and compared the performance of the new strategy with level-crossing logic. This technology was proposed as a means of reducing the energy consumption of HVAC equipment by reducing the frequency of start-stop operations. If the hourly start-stop cycling is reduced by two-thirds, the coefficient of performance of vapor compression equipment is raised an estimated 10%. The corresponding improvement for non-electric heating equipment efficiency is estimated at 6%.

This project applied pulse-width modulation (PWM) logic and a finite state machine to start and stop individual units. This control software was combined with a model of the heat transfer dynamics of a building and a transient model of HVAC equipment to study the performance of the new strategy and compare it to alternative strategies.

The metrics used to assess performance were energy consumption, peak demand, thermal comfort, and maintenance cost. The variability of the space temperature was used as a proxy for thermal comfort. Start-stop operations were used as a proxy for maintenance cost.

Objectives

The goal of this project was to determine the feasibility of reducing the energy consumption of HVAC equipment by reducing the frequency of start-stop operations. This was to be achieved by use of a newly developed control logic to coordinate the operation of multiple HVAC sub-systems. The following project objectives were established:

1. Develop new control software for operating energy-intensive, on-off, or staged equipment in buildings by adapting existing concepts for designing pulse-width modulation logic and finite state machines to this application.
2. Perform a computer simulation analysis of the performance of the control software to determine whether or not the new control strategy has energy, thermal comfort, or maintenance benefits relative to existing methods of operating this equipment.
3. Assess the change in energy efficiency as a result of the change in start-stop operations of vapor compression equipment with a target of 13% improvement, and non-electric heating equipment with a target of 6% improvement.
4. Maintain occupant thermal comfort levels.

Outcomes

1. The control software development yielded code that could be used to operate a wide variety of staged HVAC equipment in buildings.
2. The computer simulations determined that the proposed control logic had no beneficial impact on overall energy consumption, thermal comfort or maintenance costs.
3. The new control logic increased the frequency of start and stop operations by 27%.
4. The new control logic increased the size of the deviation from the space temperature set point by 11%.
5. An unanticipated outcome was the discovery that the new control logic combined with an optimized coordinator could load-level the power consumption of HVAC equipment, reducing excursions by 20% relative to level-crossing logic.

Conclusions

1. Commercialization would involve control software development. The existing code would have to be adapted to a particular platform, but no hardware would be required as long as there was an existing control communication system in place so that a coordinator running on a networked computer could supervise a number of HVAC control units.
2. Using the proposed metric for equipment efficiency, the 27% increase in frequency of start-stop operations corresponds to an estimated seven percent (7%) decrease in coefficient of performance of vapor compression equipment and a greater than one percent (1%) decrease in non-electric heating equipment efficiency.
3. Equipment manufacturers are sensitive to the increased warranty risks due to increased on-off cycling.
4. Equipment installers may be reluctant to utilize this control logic because weaker temperature and humidity control may result in decreased comfort levels.
5. For commercial businesses with high power consumption the cost of power consumed during peak generation periods is high. Using the software control logic developed by this project to level the demand load during peak periods may save on energy costs associated with exceeding a billing rate threshold but any savings may be offset by increased energy consumption, higher maintenance and lower thermal comfort.

Benefits to California

This project proposed the benefit of increased HVAC equipment efficiency derived from reduced on-off cycling. It discovered that PWM control strategy did not achieve this desired result. While the feature of load leveling by PWM control is an interesting development of this study, it is unclear to what extent California might benefit from this secondary result.

Recommendations

Additional work is needed to investigate whether or not it is possible to provide energy benefits from the new strategy and to reduce the maintenance penalty. It is possible that by operating the PWM signals asynchronously and at different frequencies the maintenance penalty could be reduced. Asynchronous operation may also yield additional energy benefits. Asynchronous operation would increase the complexity of the design of the control logic, though not necessarily the complexity of its implementation.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: <http://www.energy.ca.gov/research/innovations> and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop- ment	5 Product Develop- ment	6 Demon- stration	7 Market Transfor- mation	8 Commer- cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

There has been no activity in this area other than investigating opportunities for continued funding. To date, efforts to secure additional funding have been unsuccessful.

Engineering/technical

The idea generation was fairly mature when the proposal was first written. Additional ideas extending the original technical concepts include considering asynchronous coordination, where units do not cycle on and off at a fixed period. This approach may solve some of the drawbacks of the approach that was tested including increased temperature variance and increased number of starts and stops.

Technical analysis included reviewing the open literature for related innovations and testing the concept with computer simulation methods. This analysis and research resulted in graphs and software that could serve as the starting point for technology development

Legal/Contractual

There has been no activity in this area.

Environmental, Safety, Risk Assessments/ Quality Plans

This project recognized the need to study the impact of the innovation on temperature control performance (variation from set point), and on start-stop frequency. Technical analysis and research included these metrics because they will be important to facility managers and equipment manufacturers. Initial drafts of the following Quality Plans are needed prior to initiation of Stage 4 development activity; Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere.

Production Readiness/Commercialization

There has been no activity in this area.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

Based on our interpretation of the information provided in Appendix A, there is no clear public benefit derived from this project's research results.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)